Baryogenesis from an Earlier Phase Transition

Tim M.P. Tait

Argonne National Laboratory

In collaboration with: Jing Shu
Carlos Wagner

hep-ph/0610375

University of Arizona
December 7, 2006

The Baryon Asymmetry

- Experiments show that:

$$\eta_B \equiv \frac{n_B}{s} = 9.2^{+0.6}_{-0.4} \times 10^{-11}$$

# of baryons - # anti-baryons

Entropy density

- This number is roughly consistent as determined by the anti-protons in cosmic rays, relic abundance of baryonic matter, nucleosynthesis, and the CMB (which is currently the most precise determination.
- The SM contained the right ingredients to explain it, but fails because the EW phase transition is predicted to be second order, and the CKM phase is not sufficiently large.

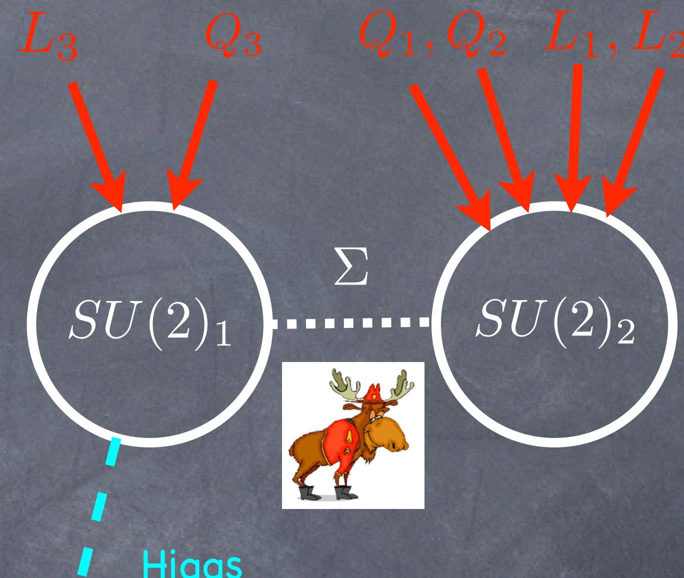
An Earlier Phase Transition?

- I would like to explore the idea that some new physics operating at slightly above the EW scale is responsible for baryogenesis.
- The particular idea I will explore is that the EW gauge interactions are extended to more symmetries. When these break down to the ordinary EW interactions (through a scaled up version of the Higgs mechanism), the phase transition generates B and L.
- The challenge is that below the new phase transition, the ordinary EW sphalerons are still going full strength. They will try to wipe out any B I generate this way.

Top-flavor

Chivukula, Simmons, Terning PRD53, 5258 (1996)
Muller, Nandi PLB383, 345 (1996)
Malkawi, Tait, Yuan PLB385, 304 (1996)

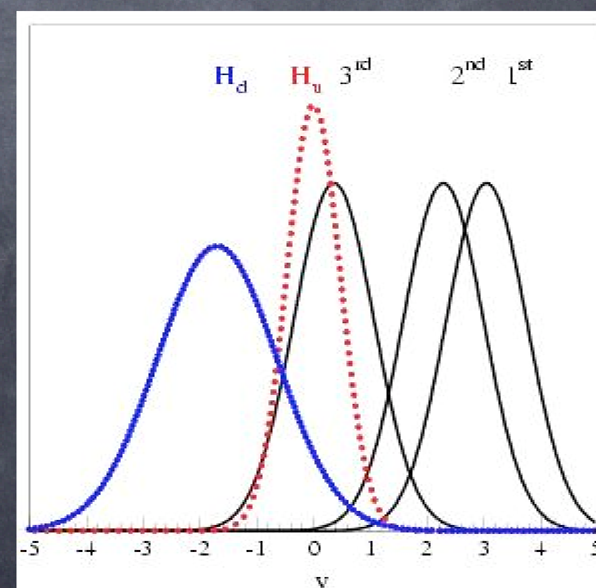
- Top-flavor expands the weak interactions into an SU(2) for the third generation, and one for the first and second generations. So we have a pair of W's and a Z'.



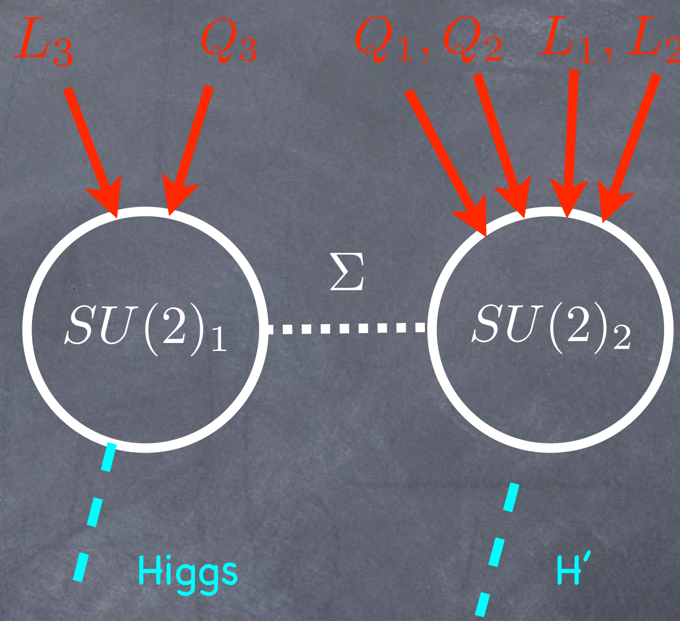
- The ordinary weak interactions are the diagonal subgroup (and are close to family universal).

- Dimensional deconstruction suggests this has similar physics to an extra-dimensional theory of flavor.

Kaplan, Tait
JHEP0006, 20, (2000)



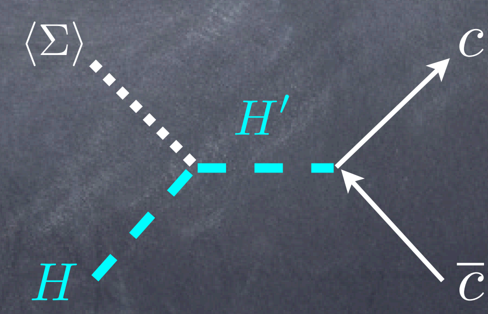
Fermion Masses



- We can generate third family Yukawa interactions very easily because the Higgs is charged under the same SU(2) as the third family doublets.
- To generate the first two family fermion masses, we include a "spectator" Higgs H'.
- The Σ Higgs acts as a bridge between H and H', giving mass to the light fermions, i.e.:

$$A_1 H' \Sigma H^\dagger + h.c$$

These interactions will turn out to be important later!

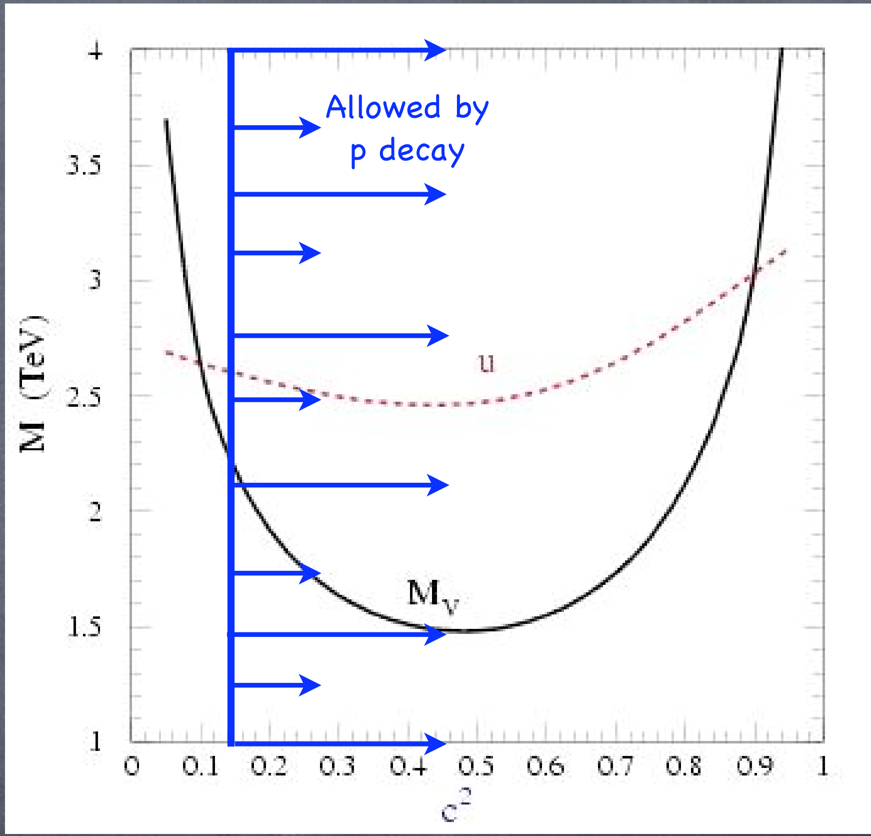


$$y_c \sim \frac{A_1 u}{M_{H'}^2} y_c'$$

Precision EW Constraints

- Precision EW constraints were considered by a number of authors.
- The most stringent bounds come from non-universality of the third family couplings to the Z (bottom and τ). We do a gobal fit to LEP and SLD.
- Instantons also bound the coupling from proton decay.

D. Morrissey, TT, C. Wagner.
PRD72:095003,2005



$$g_1 = \frac{g}{\sin\phi} \qquad g_2 = \frac{g}{\cos\phi}$$

$$M^2_{W',Z'} = \frac{g^2}{2\sin^2\phi\cos^2\phi}u^2$$

Phase Transition

- At high energies, top-flavor has two sectors of instantons, one acting on the third family and one on the first two families.
- I'll consider the limit of large coupling in the first SU(2), so I can neglect the first two families.
- The phase transition will produce third family quarks and leptons (Δ of each, with B-L=0). The baryons will quickly diffuse into all three families, because of the large quark masses and CKM angles.
- The third family lepton number is frozen in the tau and its neutrino because ν masses are so small.

B=L=0!?

- Below the top-flavor phase transition scale, the EW sphalerons are still active.
- Since B-L=0, they can set B=L=0. So they DO erase the baryon asymmetry we have generated.
- But what they can't do is change the distribution of lepton number inside each family individually.
- So we end up with:

$$B = 0; \quad L_1 = L_2 = -\frac{\Delta}{3}; \quad L_3 = \frac{2\Delta}{3}$$

- It turns out this will be good enough!

Dreiner, Ross NPB410, 188 (1993)

EW Phase Transition

- The Universe persists with no net baryon number until we reach the ordinary EW phase transition.

- At that point, masses for the fermions turn on.

- We can write the number densities of the fermions in terms of chemical potentials (in the limit T>>m):

$$L_i \approx \frac{1}{2}\mu_i T^2 \beta_i \qquad B \approx -\frac{1}{3}\mu T^2 \alpha$$

$$\beta_i \equiv 1 - \frac{1}{\pi^2}\frac{m_{l_i}^2}{T^2} \qquad \alpha \equiv 6 - \frac{3}{2\pi^2}\sum_{i=1}^{6}\frac{m_{q_i}^2}{T^2}$$

- EW sphalerons (+ fast flavor changing weak interactions) conserve three quantities:

$$\Delta_i \equiv L_i - \frac{1}{3}B \approx \frac{\mu T^2}{9}\alpha - \frac{\mu_i T^2}{2}\beta_i$$

...Resulting in B ≠ 0!

- So for any system that starts with three Δ with some values, we can compute the resulting baryon density by inverting the three equations for μ:

$$\Delta_i \equiv L_i - \frac{1}{3}B \approx \frac{\mu T^2}{9}\alpha - \frac{\mu_i T^2}{2}\beta_i$$

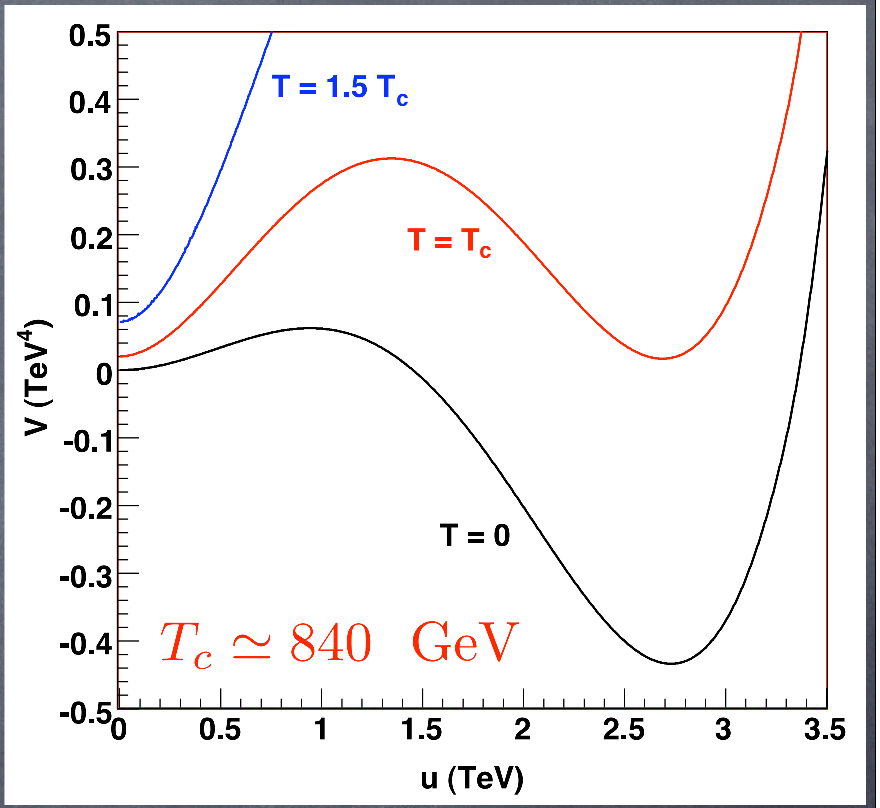
- Keeping the leading terms (assuming B-L=0), we obtain:

$$B = -\frac{4}{13\pi^2}\sum_{i=1}^{N}\Delta_i \frac{m_{l_i}^2}{T^2}$$

- Remarkably, even for B-L=0, as long as not all of the Δ's are zero, we do end up with a non-zero B. Putting in the τ lepton mass and T ~ 100 GeV, we find the final baryon asymmetry is of order: $10^{-6}\Delta_\tau$

Critical Temperature

- Having chosen the tree level parameters, we can compute the corrections to the Σ potential.
- The important corrections come from the W's and Z'. (Self-interaction corrects are small because the λ's are).



$$V(u,\theta,T) = V(u,\theta,0)_0 + V_1(u,\theta,0) + V_1(u,\theta,T)$$

$$V_1(u,\theta,0) = \frac{6}{64\pi^2}\left(\frac{g_L^2}{s^2c^2}\right)^2 u^2\left[u^2\left(\log\frac{u^2}{u_0^2}-\frac{3}{2}\right)+2u_0^2\right]$$

$$V_1(u,\theta,T) = \frac{g_i T^4}{2\pi^2}\int_0^\infty dx\cdot x^2\left\{\log\left(1-\exp^{-\sqrt{x^2+g^2u^2/(s^2c^2T^2)}}\right)\right\}$$

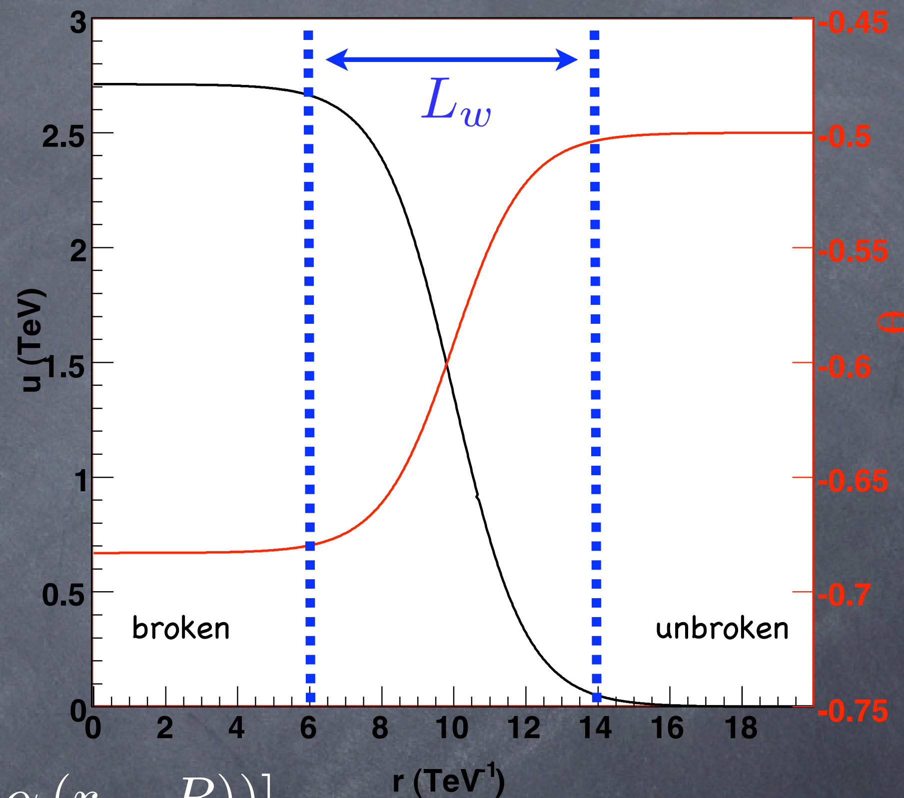
Bubble Wall Profile

- To study the parameters of the nucleated bubble, we can use the potential at the critical temperature.

- We use an ansatz (based on a 3d kink) for the VEV as a function of radius:

$$u(r) = \frac{u_c}{2}\left[1 - \mathrm{Tanh}\left(\alpha\left(r - R\right)\right)\right]$$

$$\theta(r) = \theta_{u=0} + \frac{\theta_c - \theta_{u=0}}{2}\left[1 - \mathrm{Tanh}\left(\alpha\left(r - R\right)\right)\right]$$



- We determine α variationally, by inserting the ansatz in the action at Tc and minimizing with respect to α.

$$S_3(T) = 4\pi \int dr\, r^2 \left\{ \left(\nabla\langle\sigma\rangle\right)^2 + V(\langle\sigma\rangle, T_c) \right\}$$

$$L_w \sim 10/T$$

Diffusion Equations

- Now we determine and solve the differential equations which describe the particle number densities induced by the passage of the wall.

Cohen, Kaplan, Nelson PLB336, 41 (1994)

- The diffusion equations are based on the fact that an imbalance in number densities participating in any interaction which is taking place quickly will look like a source or sink for those species which are imbalanced.
- Processes which are extremely fast will maintain chemical equilibrium, and allow us to reduce the number of species we include the equations. (Other species are related to those by equilibrium conditions).

Equilibrium Relations

- The net particle number for each species can be written in terms of a chemical potential μ:

$$n_i = k_i \mu_i \frac{T^2}{6}$$

- The k's account for the internal degrees of freedom.

$$k_Q = 6; \quad k_L = 2; \quad k_t = k_b = 3; \quad k_h = 8$$

- Fast weak/Yukawa interactions and strong instantons allow us to relate all of the light quark densities in terms of the right-handed bottom quark:

$$Q_{1L} = Q_{2L} = -2U_R = -2D_R = -2S_R = -2C_R = -2b$$

Diffusion Equations

- So the species we will consider are: Q_3, t_R, b_R, H, L_3
- The current conservation equation can be written:

$$\partial_\mu J^\mu \simeq \partial_0 n - D\vec{\partial}^2 n \simeq v_w n' - D n''$$

- where the diffusion constants D depend on the rate of interaction with the background plasma:

$$D_Q \sim D_t \sim D_b \sim 6/T \qquad D_h \sim D_L \sim 110/T$$

- and v_w is the velocity of the bubble wall as it expands, typically 0.01-0.1 for weakly coupled theories.

Diffusion Equations

- Which brings us to the diffusion equations:

$$v_w Q' - D_Q Q'' = -\Gamma_y \left[\frac{Q}{k_Q} - \frac{h}{k_h} - \frac{t}{k_t} \right] - 6\Gamma_{QCD} \left[2\frac{Q}{k_Q} - \frac{t}{k_t} - 9\frac{b}{k_b} \right]$$
$$-6\Gamma_1 \left[3\frac{Q}{k_Q} + \frac{L}{k_L} \right]$$

$$v_w t' - D_Q t'' = -\Gamma_y \left[-\frac{Q}{k_Q} + \frac{h}{k_h} + \frac{t}{k_t} \right] + 3\Gamma_{QCD} \left[2\frac{Q}{k_Q} - \frac{t}{k_t} - 9\frac{b}{k_b} \right]$$

$$v_w h' - D_h h'' = -\Gamma_y \left[-\frac{Q}{k_Q} + \frac{h}{k_h} + \frac{t}{k_t} \right] + \gamma_h$$

CP-violating source

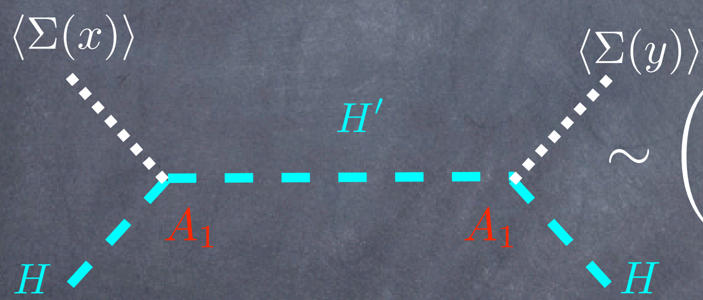
$$v_w b' - D_Q b'' = 3\Gamma_{QCD} \left[2\frac{Q}{k_Q} - \frac{t}{k_t} - 9\frac{b}{k_b} \right]$$

$$v_w L' - D_L L'' = -2\Gamma_1 \left[3\frac{Q}{k_Q} + \frac{L}{k_L} \right]$$

Γ_1 : Top-flavor sphalerons
Γ_{QCD}: strong instantons
Γ_y: Top Yukawa interaction

CP Violating Source

- The CP-violating source is induced by the bubble wall.
- The change in the VEV of Σ is accompanied by a change in the CP-violating phase.
- Σ interacts with the Higgs through terms such as:

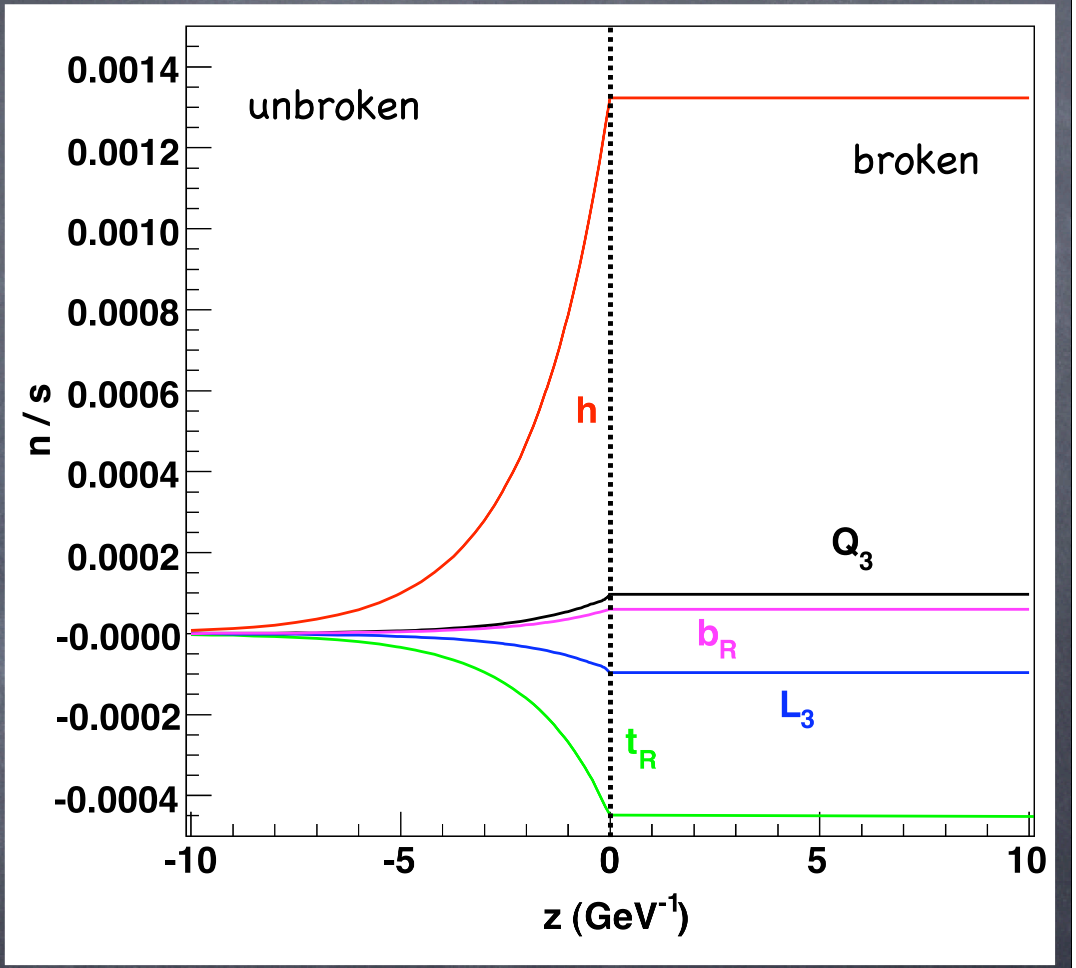


$$\sim \left(\frac{\Delta\theta}{L_w} v_w\right) u^2(x)|A_1|^2 \; \mathrm{I} \qquad \sim 10^8 \ \mathrm{GeV}^4$$

- This induces a shift in the properties of the Higgs inside and outside of the bubble, resulting in an imbalance in the Higgses and anti-Higgses transmitted/reflected from the bubble wall. The source is non-zero only in the wall.

Success!

- Solving these equations yields the profile of the particle densities.
- We place the wall at z=0. Its width is ~ 10/T ~ 10^{-2} GeV^{-1}.
- We find for the parameters we have chosen, we arrive at Δ_T of order 10^{-4}, which including the dilution of 10^{-6} yields about the right B.



(We have a numerical solution as well; it is pretty much identical)

Outlook

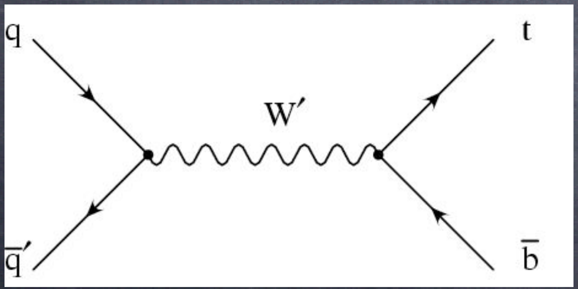
- The specific result is (of course) dependent on the choice of parameters. The value itself is not very interesting.
- What is interesting is that for "natural" values of parameters, one can obtain the right ballpark for the baryon density.
- Further, there are systematic features which decide whether or not this works in the Topflavor model:
  - A small quartic for Σ implies a light mass for the radial mode: about a factor of 10 lighter than the W'/Z' masses.
  - Large CP violation which may be visible in Σ decays (which are mostly to Higgs).

Supplemental Slides

Outlook

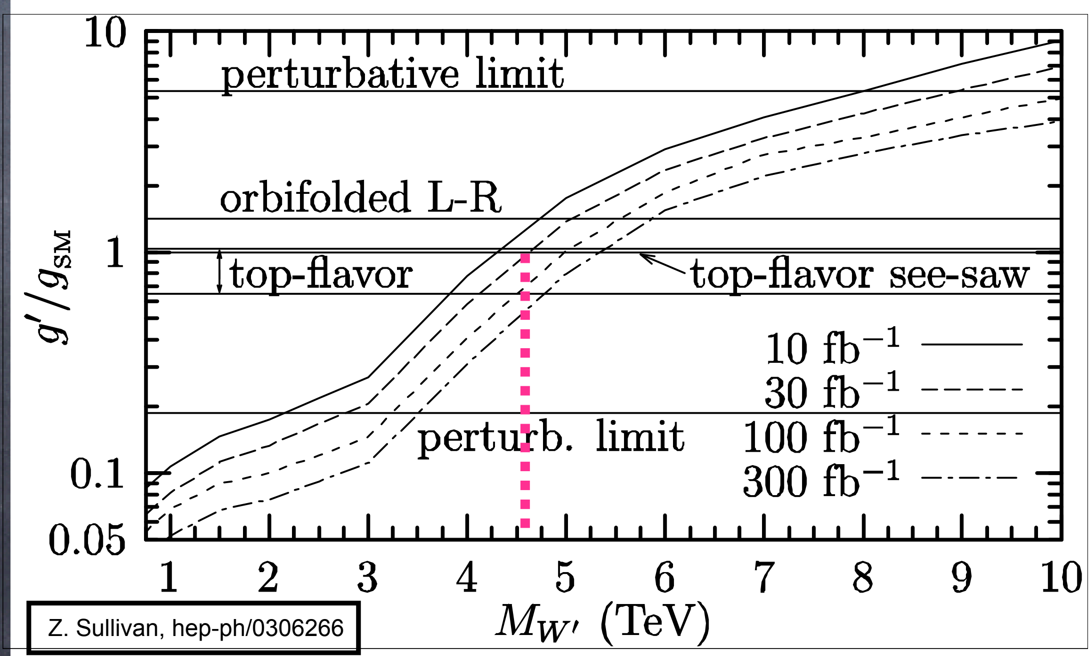
- The SU(2) x SU(2) phase transition should take place around the TeV scale, implying that the W′ and Z′s have masses accessible at the LHC.

- For example, the W′s lead to an enhancement of s-channel single top production!



E. Simmons, PRD55,5494 (1997)

TT, C.P. Yuan, PRD63, 014018 (2001)



Z. Sullivan, hep-ph/0306266